GAIN TILT CONTROL WITH MID-STAGE ATTENUATORS IN ERBIUM-DOPED FIBER AMPLIFIERS

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/089967 filed June 19, 1998 and incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to the field of optical communications and in particular to an erbium-doped fiber amplifier having gain tilt control with mid-stage attenuators.

BACKGROUND OF THE INVENTION

The demand for higher capacity transmission systems generated by the evolution of voice and data networks has led to the development of multi-wavelength, wavelength-division-multiplexed (WDM) optical communication systems having a large number of individual channels. (See, e.g., Y. Sun, J.B. Judkins, A.K. Srivastava, L. Garrett, J.L. Zyskind, J.W. Sulhoff, C. Wolf, R.M. Derosier, A.H. Gnauck, R.W. Tkach, J. Zhou, R.P. Espindola, A.M. Vengsarkar, and A.R. Chraplyvy, "Transmission of 32-WDM 10-Gb/s Channels Over 640 Km using Broad Band, Gain-Flattened Erbium-Doped Silica Fiber Amplifiers, " IEEE Photon. Tech. Lett., Vol. 9, No. 12, pp. 1652-1654, December 1997; A.K. Srivastava, Y. Sun, J.L. Zyskind, J.W. Sulhoff, C. Wolf, J.B. Judkins, J. Zhou, M. Zirngibl, R.P. Espindola, A.M. Vengsarkar, Y.P. Li, and A.R. Chraplyvy, "Error Free Transmission of 64 WDM 10-Gb/s Channels Over 520 Km of TRUEWAVE Fiber", NEED PUBLICATION DATE; and A.K. Srivastava, Y.Sun, J.W. Sulhoff, C. Wolf, M. Zirngibl, R. Monnard, A.R. Chraplyvy, A.A. Abramov, R.P. Espindola, T.A. Strasser, J.R. Pedrazzini, A. M. Vengarkar, J.L. Zyskind, J. Zhou, D.A. Ferrand, P.F. Wysocki, J.B. Judkins and Y.P. Li, "1 Tb/s Transmission of 100 WDM 10-Gb/s Channels Over 400 Km of TRUEWAVE Fiber", OFC Technical Digest, Postdeadline Papers, PD 10-1-10-4, San Jose, CA, February 22-27, 1998).

In an attempt to increase the capacity of these WDM optical communications systems and networks, it has been shown that it is generally desirable to have as many wavelength-division multiplexed (WDM) optical channels as possible within a given WDM system. As can be appreciated, broad

5   band optical amplifiers are required to implement these "dense" WDM (DWDM) optical systems and networks.

Appropriately, rare earth-doped optical fiber amplifiers are used to amplify optical signals used in communications systems and networks. These rare earth-doped optical fiber amplifiers are found to be cost effective, exhibit

10   low-noise, provide relatively large bandwidth which is not polarization dependent, display substantially reduced crosstalk, and present low insertion losses at relevant operating wavelengths. As a result of their favorable characteristics, rare earth-doped optical fiber amplifiers, e.g., erbium-doped fiber amplifiers (EDFAs), are replacing current optoelectronic regenerators in

15   many optical lightwave communications systems and in particular, wavelength-division-multiplexed (WDM) optical communications systems and networks.

To support the growth in the number of channels in WDM transmission systems and networks, optical amplifiers having wide bandwidths are required. Accordingly, the gain of the amplifiers should be uniform over the entire WDM

20   bandwidth so that the channels may be transmitted without impairment.

As is known in the art, desirable gain characteristics may be realized through the use of gain equalization filters, such as long period gratings (See, e.g., A.M. Vengsarkar, P.J. Jemaire, J.B. Judkins, V. Bhatia, T. Erdogan, and J.E. Snipe, "Long-Period Fiber Gratings as Band-Rejection Filters",

25   J.Lightwave Tech., Vol. 14, No. 1, pp. 58-65, January, 1996). Unfortunately, when such wide band optical amplifiers are used in actual systems, the system power "flatness" may be affected by a number of factors such as spectral loss in the transmission or dispersion compensation fiber, spectral loss in passive components, variation in input signal power spectrum and Raman effect in the

30   fiber (See, e.g., A.R. Chraplyvy and P.S. Henry, "Optical Power Limits In

Multi-Channel Wavelength-Division-Multiplexed Systems Due to Stimulated Raman Scattering", Electron. Lett., Vol. 20, No.2, pp 58-59, January 1984).

To a first order, the deviation from the "ideal flatness" for wide band optical amplifier may be approximated to a linear tilt in the signal power spectrum. Consequently, methods and apparatus for controlling the tilt are desired to produce wide band optical amplifiers having desirable operating characteristics.

SUMMARY OF THE INVENTION

We have discovered a method for controlling the gain tilt of an optical amplifier by utilizing a mid-stage attenuator positioned within the amplifier. The mid-stage attenuator mitigates channel power spectral tilt. By changing the loss of the attenuator, an average inversion level of erbium-doped fiber can be adjusted, which further affects the gain tilt in the EDFA gain spectrum.

Further features and advantages of the present invention, as well as the structure and operation of various embodiments of the present invention are described in detail below with reference to the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWING

Fig. 1(a) is a schematic of a two stage optical amplifier with a mid-stage variable optical attenuator according to the present invention;

Fig. 1(b) is a plot of the gain vs. wavelength of the optical amplifier of Fig. 1;

Fig. 2 is a schematic of an experimental setup for gain tilt control according to the present invention;

Fig. 3(a) is a plot of input power spectrum of 18 WDM channels with both +4dB and –2dB tilt;

Fig. 3(b) is a plot of tilt corrected output spectra after amplification by amplifier according to the present invention;

Fig. 4 is a plot showing necessary attenuator loss to obtain a flat output spectrum for different signal tilts in the range of −4dB to 4dB; and

Fig. 5 is a plot showing necessary attenuator loss at constant gain operation for different signal tilts in the range of −4dB to 4dB.

5   **DETAILED DESCRIPTION OF THE INVENTION**

Fig. 1(a) illustrates the basic principle of our optical amplifier and inventive method. The amplifier shown there 100, is divided primarily into two stages and comprises optical isolators (OI) 101, sections of erbium-doped optical fiber (EDF) 103, wavelength selective couplers (WSC) 105, gain
10   equalization filter (GEF) 107, variable attenuator (VA) 109 and 980nm and 1480nm optical pumps 111 and 113, respectively. The amplifier exhibits broadband, large dynamic range, high power characteristics desirable for wavelength division multiplexed transmission of optical signals.

With continued reference to Fig. 1(a), optical signals (not shown) enter
15   the optical amplifier 100 through input port 110 and exit from output port 120, with the output port 120 being "downstream" of the input port 110. Optical isolators 101, attenuators 109, GEFs 107, and WSCs 105, are generally known in the art, some of which are commercially available. Furthermore, those skilled in the art know that it is conventional, but optional, to place optical isolators
20   respectively upstream and downstream of an EDFA.

Fig. 1(b) shows a plot of gain vs. wavelength for the optical amplifier of Fig. 1(a). As is shown, the amplifier exhibits uniform gain characteristics over 35nm of bandwidth (1526nm–1561nm). The gain spectrum may be kept flat for a range of input power levels by adjusting the variable
25   attenuator 109. With an input power of −4dBm and the attenuator set to a minimum, the gain is 24dB with 12dB of gain compression with a noise figure of approximately 5dB.

An experimental setup for gain tilt control according to the present invention is shown schematically in Fig. 2. As is shown, two optical amplifiers
30   are used therein. Specifically, a first erbium-doped fiber amplifier 210 is used to

prepare an input signal spectrum with simulated power tilt for a second erbium-doped fiber amplifier 220. A waveguide grating router 230, was used to multiplex 18 WDM signals (λ_1 - λ_{18}) that originated from external lasers (not shown). For our demonstrative purposes, the signal channels ranged from 1531.4 to 1558.6nm with 200GHz channel separation resulting in a total bandwidth of approximately 27nm.

The signal power of the channels was then sent through an attenuator/power meter 240 which controlled the input power to the first (preparation) amplifier 210 which is constructed like amplifier 100 shown in Fig. 1. With further reference to Fig. 1, the attenuator 109 within a mid-stage of amplifier 100 may be tuned to obtain a total power tilt between –4dB and 4dB between the shortest and longest wavelength channels. For the purposes of our evaluation, the signal power spectral tilt input to the second (test) amplifier 220 was monitored by an optical spectrum analyzer 260 and a second attenuator/power meter 250 was used to adjust the total input power entering the test amplifier 220.

As is used herein, positive tilt is the power tilt with low power in the short wavelength side and high power in the long wavelength side. Accordingly, negative tilt is the reverse situation.

The input spectrum of the 18 WDM channels with both +4dB and –2dB tilt is shown in Fig. 3(a). With a suitable adjustment of the mid-stage variable optical attenuator in the test amplifier 220, the power spectrum tilt can be compensated. Shown in Fig. 3(b) are the tilt corrected output spectra after the test amplifier 220 for both 4dB and –2dB tilt in the input spectrum. As shown in that Figure, the tilt in the input spectrum can be completely mitigated by changing the mid-stage attenuator loss in both cases.

The attenuator loss needed to obtain the flat output spectrum for different input signal tilts in the range of –4dB to +4dB when the total input power is fixed at 0.4dBm is shown in Fig. 4. At this input power level, the attenuator was set to 4.5dB to produce a flat output spectrum for a flat input spectrum.

When the power spectrum tilt is between –2 and 4dB, the compensation can be completed by adjusting the attenuator between 0 and 17 dB. A penalty results however, in that the output power decreases when attenuator loss is increased. In the case of –4dB tilt, the minimum loss in the attenuator is not

5 sufficient to flatten the output power spectrum.

Similar evaluations were made for constant gain operation, as shown in Fig. 5. In this evaluation, the input power was adjusted to maintain a constant gain of 21.4dB at each power tilt condition. To produce a flat output spectrum, the attenuator was set to 2dB for a flat input spectrum. Total compensation

10 was realized with positive tilt while partial compensation was realized for input tilt of –2dB when the attenuator was set to its minimum value. Similar to the case of constant total input power, the total output power decreases with increasing attenuation.

Various additional modifications of this invention will occur to those

15 skilled in the art. Nevertheless, all deviations from the specific teachings of this specification that basically rely upon the principles and their equivalents through which the art has been advanced are properly considered within the scope of the invention as described and claimed.